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Explosion protection for coal grinding plant.

What should really be done?

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Explosion protection for coal grinding plants. What should really be done?

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Summary

The recent history of coal grinding around the world shows a scattered picture concerning the implementation of explosion venting, the "last resort" form of explosion protection.

This text deals with the possible reasons why the usual engineering concepts fail to conform to existing explosion venting standards, and the difficulties that engineers face when dealing with the implementation of explosion vents to match the requirements of standards.

The existing guides and codes are based on explosion protection knowledge obtained mainly from test work on a much smaller scale than the usual size of cement industry equipment. Only a few publications of scientific work are available that may form a suitable basis for related standardisation work. The result is that the design of coal grinding plant to operate on the cement manufacturing scale is inadequately covered by existing guidance and codes. These provide warnings but, unfortunately, do not instruct clearly and comprehensively.

Accidents, for a number of reasons, are not widely publicised and systematically investigated, which means that no evaluation takes place. Therefore, no information derived from practice is available.

This publication deals with the difficulties which designers of coal mill plants for cement production face, when they agree to refer to existing guides and codes. It also aims to offer guidance for clearer understanding of the warnings given in the codes, by putting them into context and relating them to practice with the help of examples.

Last, but not least, the publication deals with a way to correctly apply explosion vents, as still the most effective and easily-applied safety measure, offering examples of its use. It explains the basis of this technique, which is not yet supported by guidelines. On the other hand, it provides explanations of where and how the technique deals effectively with the issues referred to by the warnings in the standards. It also indicates where the existing guidelines would require substantial further development to cover the needs of industry by providing much needed answers to old questions.

Coal and other solid fuels will continue to play an important role in cement making. Although modern process control and good engineering can and should do much to prevent explosions, some means of protection will remain necessary as a last resort in the case of technical failure of process control or plants. Explosion venting is the easiest last resort technique to apply.

This being an accepted fact, and given the underlying rules of efficiency, productivity, and quality assurance of ISO 9002, it is only natural that the industry should implement and maintain explosion vents correctly, in order to optimally protect personnel and limit plant damage and stoppage.

Why will explosions occur in coal mill systems?

Let us start with the definition of an explosion.

> An explosion is a very fast combustion process that heats air, with the result that the air expands and produces pressure, with subsequent damage to equipment. In a situation in which no such damage occurs, the rapid combustion can be referred to as deflagration, e.g., the case of unconfined combustion in which pressure is immediately dissipated into the atmosphere. What we discuss here is the confined situation, in which the pressure may become hazardous in terms of potential rupture of the confining walls.

The maximum pressure in a typical confined fuel/air mixture explosion will usually be in the range 4 -9 bar g/60 - 130 psi g, as long as ignition takes place under atmospheric pressure conditions. Ignited under pressure, the resulting explosion pressure may be much higher.

What can burn so rapidly as to cause hazardous pressure rise?

Answer: Air/Fuel mixtures. Only fine fuel particles, which are dispersed in air, will enable combustion to proceed so fast that the resulting pressure rise is sufficiently rapid to be called a deflagration or explosion.

Explosions in coal mill systems are confined explosions, which means that the pressure effects must be dealt with by protective techniques to prevent the pressure rise from exceeding the strength of the plant, either by venting the expanded air into the atmosphere or by suppressing the combustion. Smaller sections of the plant, such as intermediate hoppers, can be built with the capacity to withstand the maximum possible explosion pressure. This way of dealing with the hazard is a technique called *containment*.

We will not discuss containment further, because in coal grinding technology, containment would only be applicable to smaller vessels and pipe ducts shorter than those usually found in coal mill systems - with the exception of those small hoppers which form parts of fuel dosing systems, e.g., the hoppers of loss-in-weight feeders. Such smaller 10 bar pressure shock resistant auxiliary feeder hoppers can be found in many coal plants.

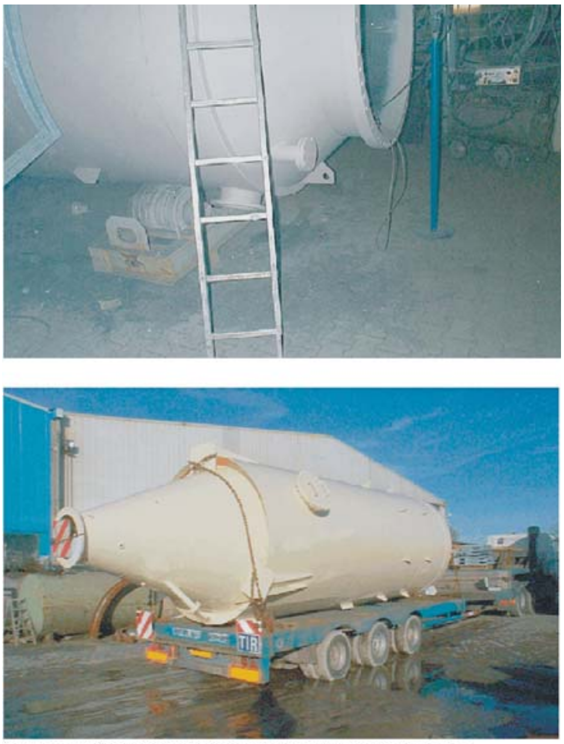


fig. 1 small silo built to contain explosion induced pressure rise

Another technique that we will only briefly refer to is *explosion suppression*. This protective technique is quite common in the food and chemical sectors.

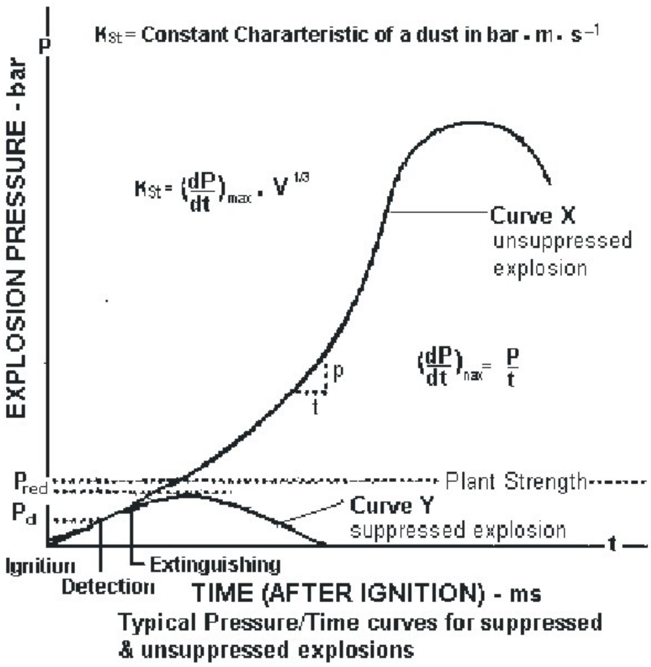


fig.2
pressure rise curve during explosion suppression

This effective protective technique has not become common in the cement industry, because the conditions in a cement plant are too unfavourable for the sophisticated and sensitive equipment required, which demands expensive regular maintenance by experts.

Explosion suppression employs pressure and/or ignition source detectors. A sensitive electronic control system will then trigger the rapid injection of a suppressing agent, which is held in strategically positioned, relatively small, pressurised buffer tanks which are attached externally to the protected enclosure. The suppressing agent, which normally consists of powdered monoammonium phosphate, will rapidly quench combustion to the extent that the pressure will not exceed a predetermined value, which the design strength of the plant has been designed to tolerate.

fig 3
pressure buffer tanks for suppression agent installed on the wall of a dryer

What is explosion venting?

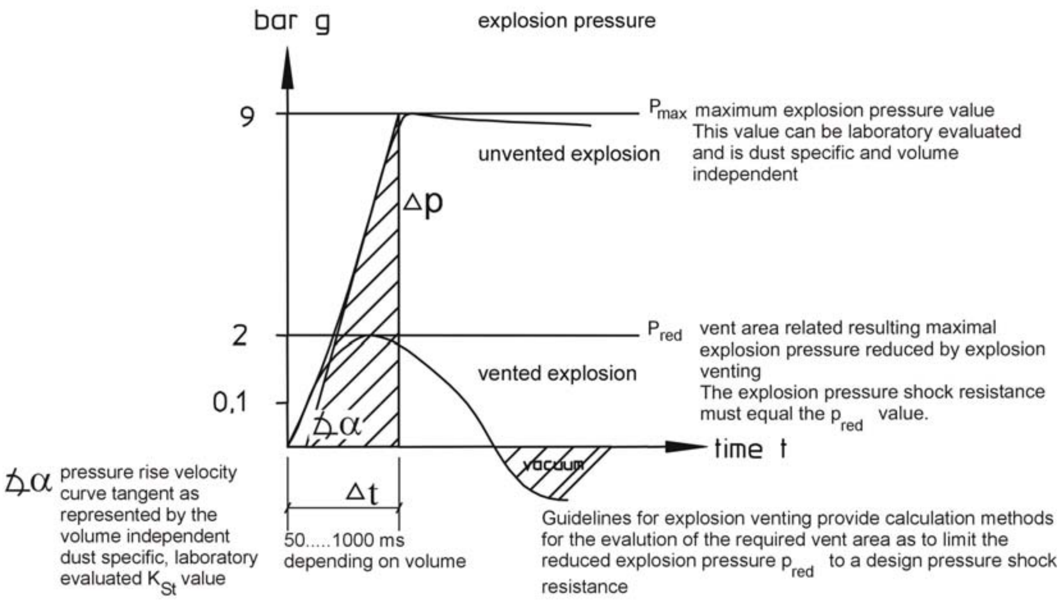


fig. 4 explosion pressure development and the effects of venting

Explosion venting can be defined as a method of interrupting the rise of explosion induced pressure inside an enclosure by connecting the enclosed volume with the infinite volume of the surrounding atmosphere, into which the pressure inside the enclosure dissipates.

Under normal conditions, the vent apertures are covered and the enclosure is isolated from the atmosphere, but if internal pressure rises, the forces will open the apertures by ejecting the covers (which should be prevented from turning into projectiles).

In the case of a vented explosion, the pressure rise versus time curve will be identical with that of a contained explosion until the moment that the vent or vents open.
This moment will occur on reaching the activation pressure of the covers, referred to as p_{stat} (static activation pressure).

From this point in time, the pressure rise curve will become less steep, which means that the rate of pressure rise gradually decreases and the final pressure value will be reduced. This takes place in a fraction of a second.

The resulting reduced explosion pressure is referred to as p_{red} (red for reduced).

The values p_{max} and K_{St} are fuel-specific values which can be determined by means of standardised laboratory tests. The values p_{max} and K_{St} must be used as input parameters when the necessary size of a vent area is calculated for a certain industrial scenario. The supplier of a particular fuel will have to provide these figures.

For the solid fuels commonly used in the cement making process, the p_{max} value will be in the range 4 - 9 bar g for a range of fuels, running from petcoke (with a low burning velocity) through various more reactive coals with high volatile contents, up to coals and lignites with a very high reactivity.

The K_{St} value, which represents the pressure rise velocity, or $\Delta P/\Delta t$, can vary between 40 and 200 bar.m.s^{-1}. This unit may look a little confusing, as one would rather expect a unit like bar/s, which would be easier to understand.

The reason for using the unit bar.m.s^{-1} is that there is a need to classify fuels independently from the volumes of the enclosures in which they are being handled, in spite of the known influence of the volume of an enclosure on the rate of pressure rise, dP/dt. In large enclosures, the pressure rise will proceed more slowly than in smaller enclosures, in which p_{max} will be reached in as short a time span as 60 - 80 ms. The interdependency between the rate of pressure rise and the volume is known as the cubic law:

$$(dP/dt)_{max} \bullet V^{1/3} = const = K_{St}$$

The values of both the fuel-specific, volume independent values p_{max} and K_{St} represent the combination of specific burning characteristics, particle size distribution and particle humidity present in a laboratory sample of a particular fuel. In practical plant operation, the values for a fuel will vary, depending on the actual conditions.

Explosion venting requires no activation mechanisms or detectors. It responds to the internal pressure of an enclosure and is activated by the forces resulting from the pressure. This makes it a relatively simple and dependable technique. Fig. 4a shows how explosion venting looks in practice:

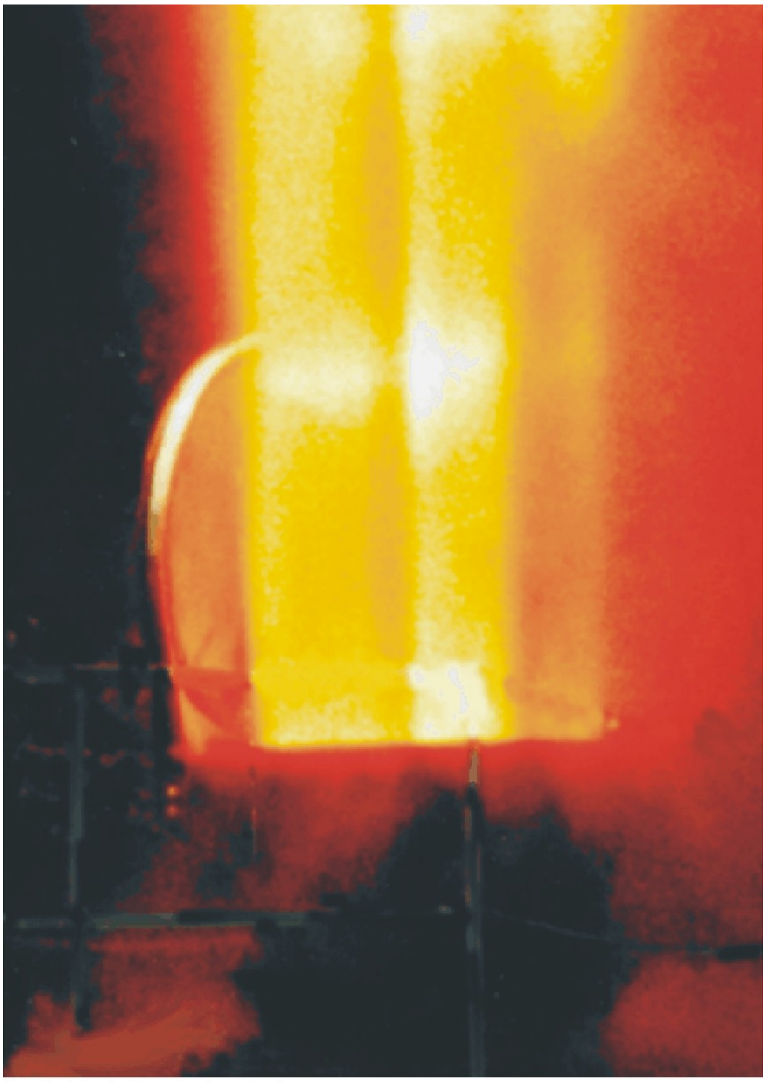
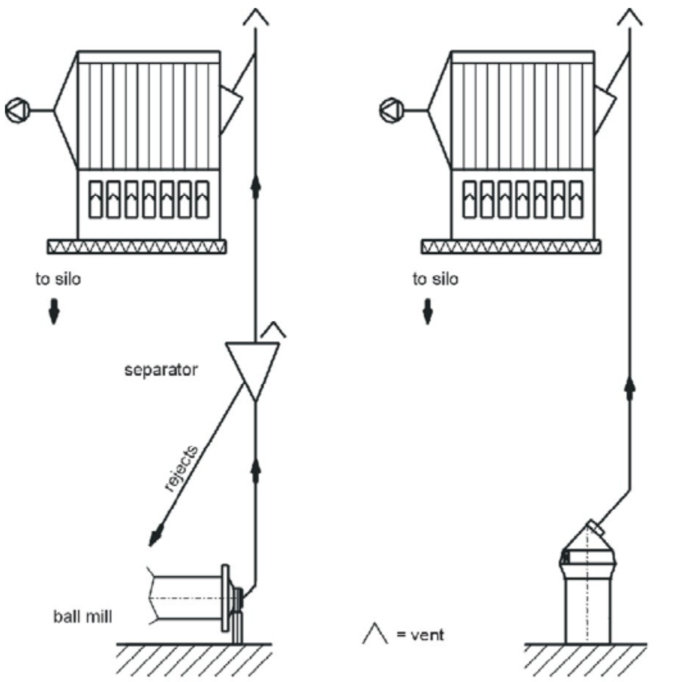


fig. 4a blast of vented explosion

In common to both ball mill and vertical coal mill systems, the normal process conditions inside the mill chamber cause ground coal particles to be lifted by air and to form an air/dust dispersion. The ground particles will be different in particle size, with a proportion of fine dust that is difficult to control.



usual ball mill system for fuel with the usual explosion vents ***insufficient!***

usual vertical mill system for fuel with the usual explosion vents ***insufficient*** !

fig. 5
typical indirect- (or storage-) firing ball mill system and typical indirect- (or storage-) vertical coal mill system simplified flow sheets with indication of explosion vents

Most explosions in coal mill plants have their initial ignition location within the mill chamber. This is because the mill chamber is the section of the plant in which the conditions for the ignition of air dispersed fuel are most favourable, as well as the risk that tramp metal gets trapped in the grinding media. Also, grinding causes impact and friction.

Before we enter any deeper into this topic, it should be clarified that, with respect to coal grinding in the cement industry, we should solely refer to *indirect firing* or *storage firing*, rather than to *direct firing*. Direct firing coal mill systems in the cement industry are becoming rare, as this process causes difficulties in controlling the accuracy of fuel feeding to the burner.

The indirect and direct firing system in this context should be distinguished as follows:

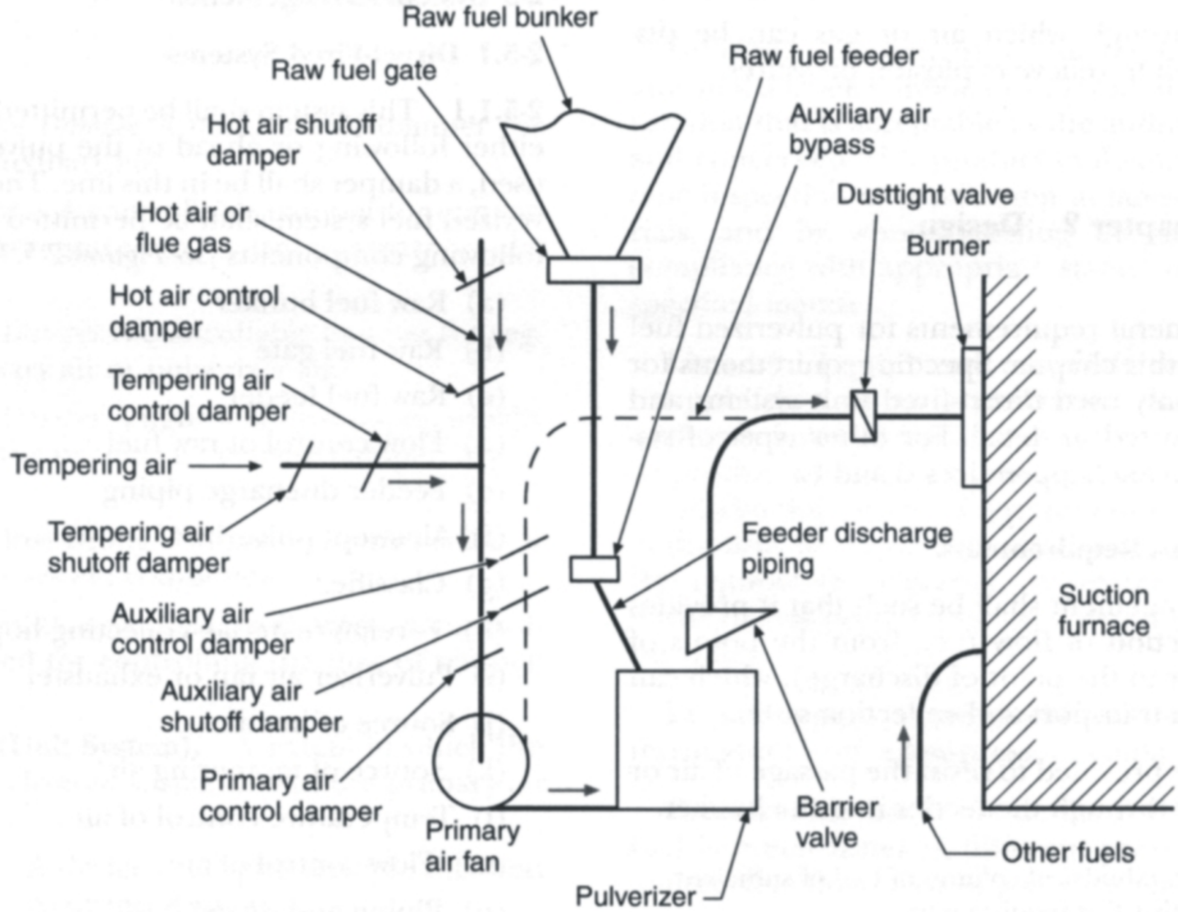


fig 6
source: NFPA 85

Direct firing coal mill plant is what is installed in most power generation facilities. The coal mill is operated as an air-swept mill and “blows” directly into the combustion zone of the steam boiler, via a pipeline connection.

In case of an explosion, normally as consequence of ignition within the mill chamber, there will be explosion propagation towards the boiler. The combustion “cloud” will propagate to where it finds more fuel, therefore, through the pipeline to the boiler, assisted by the explosion induced internal pressure in the mill chamber and the basic flow velocity which is inherent to air swept mill systems.

Once the flame jet has entered the boiler combustion zone, the problem vanishes. The flame does no cause any harm there, and the pressure shock wave dissipates in the large boiler chamber volume.

The dust cloud involved in the rapid combustion within the mill chamber and mill-to-boiler duct will not be large and is partly burned by the time the propagation reaches the boiler.

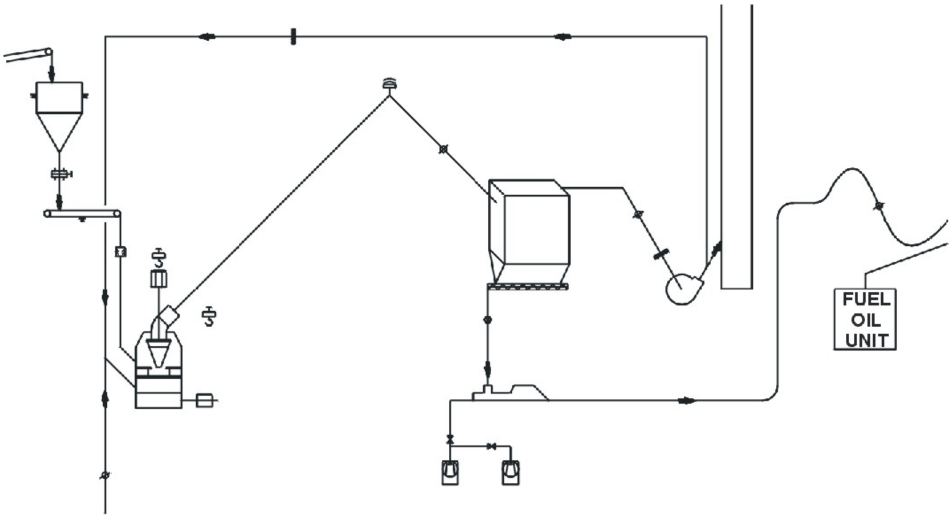


fig.7
simplified general flow sheet of an indirect- or storage firing system

An indirect (or storage) firing plant is what is installed in most modern cement works. The fine particles continuously produced by the mill are pneumatically conveyed to one or more separation stages, in which the fuel particles are separated from the conveying air. The separation stages are connected to one or more storage vessels, from which the pulverised fuel is extracted and dosed to the burner.

The problem with this kind of process is that if a mill induced explosion starts to propagate, it will encounter the next separator (or cyclone, or dust collector) on its course. This will result in ignition of the dust clouds in this enclosure, under adverse conditions to which we will refer later.

Usually, the grinding process in the cement industry (and in the steel and other industries) is combined with coal drying. Hot, exhaust air low in O_2 content from the kiln process and/or its preheating stage, along with air from other sources, enters the mill in order to contribute to the drying process with its thermal energy and to dilute the O_2 content of the mix of process air flowing through the system.

In theory, by keeping the O_2 level low (normally below 12%), the possibility of an explosion can be excluded.

The ground coal particles are suspended in the process air flowing through the mill and are conveyed upwards by the flow. Normally, the storage location is a silo, which needs to be at some height above the ground.

The pulverized coal's flow behaviour requires a 70° discharge funnel. This funnel substantially increases the height of the storage silo, which will additionally have a burner feeding system beneath it, with a height of several meters, adding to the silo system's overall height by several meters.
The combined height of the pulverised coal feeder, storage silo (with cone) and air/coal separation system; all of which form part of the grinding system in a modern, large cement plant, can be well in excess of 50 m.

Typical vertical roller mill coal grinding system with long mill-to-dust separator duct, illustrating considerable overall height of system

fig.8 explosion triangle

What enables an explosion to occur? How will an explosion occur?

The three conditions shown in the explosion triangle must be fulfilled simultaneously:
There must be fuel. There must be sufficient O_2. There must be an ignition source.

We should fine-tune this a little:

In order for an explosion to occur, the fuel must be finely dispersed in air of sufficient O_2 content, in the right fuel/air concentration range - and the ignition source must be powerful enough.

How closely does coal grinding in the cement industry come to this fine-tuned set of conditions, be it in a ball mill system or in a vertical mill system?

1) The fuel side of the triangle – is always there, although possibly not always in the most dangerous concentration.

   The dispersed fuel is there (in the mill chamber) during start-up, production and shut-off. Its concentration in the air may or may not be continuously within the range in which the ignition of a dust explosion would be possible.
   The concentration of dispersed fine fuel particles may, at times, fluctuate and be highly uncontrollable both in terms of time and location within the mill chamber.
   The occurrence of the "suitable" fuel condition (in terms of explosiveness) cannot be avoided.

2) The O_2 side of the triangle – can be controlled or at least perfectly monitored.

   Theoretically, it is not a problem to control the O_2 content of an air flow. But in practical operation of a cement plant coal mill system, O_2 control is prone to difficulties varying from staff sloppiness to mechanical failures of different kinds.

   Since almost all coal mill systems are operated under negative pressure (in order to not emit dust, among other reasons), the fan at the clean air outlet of the dust collector may suck atmospheric air into the system, perhaps unnoticed, via leakage in the duct joints, from the mill chamber up to the dust collector bag house.

   Although sophisticated and reliable O_2 concentration monitoring equipment can be, and often is, installed, it remains difficult to prevent, at all times, a “sufficient O_2 concentration” from building up.

3) The ignition side of the triangle – cannot be fully controlled.

Smoldering nests in the mill can be reliably detected by means of CO monitoring. To a great extend, though not fully, tramp metal can be separated before it enters the mill. The hot air intake is sufficiently hot to serve as an ignition source. And the grinding process works on the basis of impact and friction.

The difficulty of avoiding too high a concentration of O_2, as well as the permanent ignition sources in the mill chamber, demand the implementation of at least one additional protection technique as a last resort.

After this introduction, in which we have discussed explosions in a very general way, we can start to discuss the specific characteristics of explosions in coal grinding systems.

We will start with a closer look at what the main existing guidelines and standards say.

The NFPA 69[1] "Standard on Explosion Prevention" would allow dilution to reduce the concentration of O_2 in the process air as the sole protective measure. More protection would not be required. The wording of the relevant section is as follows:

quoted text NFPA 69 (1997 edition)	*comments:*
2-1 Application 2-1.1* The technique for oxidant concentration reduction for def1agration prevention can be considered for application to any system where a mixture of oxidant and f1ammable material is confined to an enclosure within which the oxidant concentration can be controlled. The system shall be maintained at an oxidant concentration low enough to prevent a deflagration. **2-2 Design and Operating Requirements** 2-2.1 The following factors shall be considered in the design of a system to reduce the oxidant concentration: (a) Required reduction in oxidant concentration (b) Variations in the process, process temperature, and materials processed (c) Purge gas supply source and equipment installation (d) Compatibility of the purge gas with the process (e) Operating controls (f) Maintenance. inspection. and testing (g) Leakage of purge gas to surrounding areas (h) Need for breathing apparatus by personnel	*In a typical coal mill plant in the cement industry this technique will be applied as the "first resort", using hot air with a low O_2 content to dilute the process air. However, due to the prevailing conditions in the cement industry, the system will not be fail-safe to the degree laid down in sub-chapter* 2-2, *which rather refers to systems operated under purge gas (like CO_2 or N_2), which are normally much smaller than typical coal grinding plant in the cement industry. Hence, in the typical coal mill plant in the cement industry, explosion venting will be implemented* as *last resort protection.*
unquote	
NOTICE (as per NFPA 69): An asterix (*) following the number or letter designating a paragraph indicates that explanatory material on the paragraph can be found in Appendix A. Appendix A says: **Oxidant Concentration Reduction.** The technique of maintaining the concentration of the oxidant in a closed space below the concentration required for an ignition to occur.	

[1] NFPA = National Fire Protection Association

Since, in practice, the prevention technique **Oxidant Concentration Reduction** can only be realized with extreme difficulty on a 24 h/day failsafe basis, a suitable solution has had to be found. For years, the engineering industry has been using explosion venting as the ideal, additional, last resort means of protection.

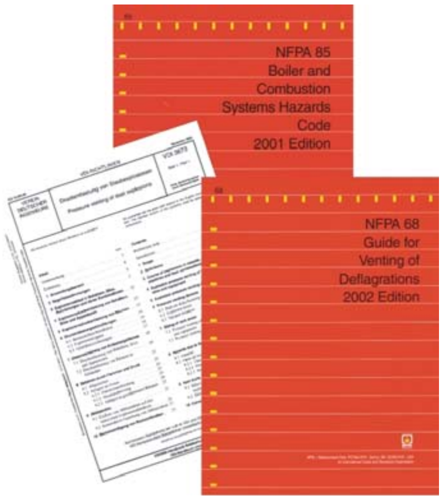
Explosion vents, which respond to the system's excess of internal pressure, need no external source of energy and no triggering by monitoring and control systems. However, although their basic technology is simple, their application and design are not.

In cement industry coal mills and their heavy duty environment, explosion vents have to be of rigid construction and be tightly sealed in order to prevent ingress of atmospheric air into the vacuum system. Their seals must be capable of functioning permanently under elastomer-unfriendly temperature conditions. Explosion vents must be resistant against a fluctuating vacuum, as well as against corrosion and wear. Despite this, their venting element must have little mass.

Their original activation pressure value plays an important role in the venting process and must be kept constant over long periods, despite temperature fluctuations and dust deposits. Last, but not least, explosion vents must work dependably in the case of an explosion, without any disintegrating parts which might becoming dangerous missiles.

The guidelines concerning explosion venting deal with these matters, although unfortunately, as far as coal mill plants are concerned, they do not go beyond general statements. A possible explanation could be that coal mill plants, from the point of their sheer size, are so much bigger than anything that experts have ever been able to thoroughly investigate, that synchronisation between expertise and practice has never taken place, due to a lack of links.

Certainly, it is extremely difficult and costly to carry out explosion tests in large plants. It is very difficult to run explosion tests under controlled, reproducible conditions in a small test facility, and in a large plant, under simulated production conditions, it is even more difficult. The cost would be enormous. However, we will make use of the extremely interesting information won from such rare tests as described later, after we have looked more closely at the applicable guides and codes.



VDI 3673 "Guidelines for Pressure Venting of Dust Explosions"

In its (latest) November 2002 version the German/Swiss originated Guidance, VDI 3673, as issued by the VDI[2], says the following regarding "explosion pressure venting of vessels interconnected with pipelines", chapters 3, 11 and 12, pages 12, 28 and 29, respectively:

[2] VDI = Verein Deutscher Ingenieure ("German Association of Engineers"), in this case their working group Kommission zur Reinhaltung der Luft ("Commission on Air Pollution").

Quoted text VDI 3673 (11/2002)	*comments:*
3 Course of explosions in vessels, silos, pipelines and their combinations	
When considering the propagation of a flame front and the rise in pressure during a dust explosion, one has to differentiate between: • flame propagation in vessels $L/D_E = 1$ • flame propagation in vessels, silos and pipelines $L/D_E > 1$	*In this context, the pipelines are the object of interest.*
Generally the velocity of flame propagation during dust explosions in vessels $L/D_E = 1$ remains small relative to the sonic velocity so that no local pressure differences occur in closed vessels. The maximum explosion overpressure may reach ten times the initial starting pressure. Such a value may be markedly exceeded with some dusts [1]. Obstructions may increase the vehemence of the explosion.	
In pipelines the flame propagation increases with growing pipe length. Some dusts, especially the ones with medium or high K_{St} value, may behave in a detonation-like fashion, e.g. if the explosion is transmitted out of a closed vessel and into a closed pipeline. In such cases the flame front propagates at supersonic speed (detonation). The pressure exerted locally on the pipe wall may reach a multiple of the explosion overpressure for a short time [29 to 30]. Even higher pressures may occur at end flanges and pipe bends due to pressure piling of the explosible mixture ahead of the arrival of the flame front. The combination vessel/pipeline predominates in practise. Examples are:	*In coal mill systems, as used in the cement industry, the pipe length can be considerable. It is not so much the question of whether a detonation-like propagation will occur. Any accelerated flame propagation would constitute a real hazard and an engineering challenge.*
• silos, milling and drying devices with downstream dust collectors • local and general dust collection • combination of storage, mixing and process vessels with pipelines	*The examples speak for themselves.*
In such a combination, where the dust explosion propagates from one vessel to another through a pipeline, the reaction may be more violent and result in a higher pressure than in a single vessel. The propagation of an explosion can be prevented or the effect can be limited through the measure “explosion decoupling” [1; 2; 33].	*In a cement plant coal mill system, the process vessels are the mill, the separator (if provided) and the dust collector.*
Unquote	

NOTICE: The numbers in square brackets [ ] refer to the bibliography on page 43 of VDI 3673.

[1] *Bartknecht, W.*: Explosionsschutz: Grundlagen und Anwendung. Berlin, Heidelberg, New York: Springer 1993

[2] VDI 2263: 1992-05 Staubbrände und Staubexplosionen; Gefahren - Beurteilung - Schutzmaßnahmen. Berlin: Beuth Verlag

[29] *Vogl, A*: Ablauf von Staubexplosionen in pneumatischen Saug-Flug-Förderanlagen. D82 Dissertation RWTH Aachen, Forschungsgesellschaft für angewandte Systemsicherheit und Arbeitsmedizin (FSA), Heidelberg: Asanger Verlag 1995

[30] *Vogl, A*: Flame Propagation in Pipes of Pneumatic Conveying Systems and Exhaust Equipment. American Institute of Chemical Engineers, Process Safety Progress, 15 (1996) No 4, pp. 219/226

[33] DIN EN 1127-1: 1997-10 Explosionsfähige Atmosphären: Explosionsschutz Teil 1: Grundlagen und Methodik. Deutsche Fassung EN 1127-1: 1997. Berlin: Beuth Verlag

quoted text VDI 3673 (11/2002)	*Comments:*
11 Explosion pressure venting of vessels interconnected with pipelines Vent areas determined by the Equations (3) and (4) are too small if the dust explosion propagates from one vessel into another through a pipeline. Increased turbulence, pressure piling and broad flame jet ignition may result in an increased explosion violence, especially with duct length > 6 m. This results in an elevated maximum reduced explosion overpressure. Measures for explosion decoupling in the connecting pipelines are therefore needed [1; 2]. In accordance with the present technology the protective measure explosion venting can be used for pipelines having a nominal diameter DN 300 and a connecting length up to 6 m, in accordance with the following criteria: • The venting device is to be designed for a low static activation pressure (p_{stat} < 0.2 bar). • Both vessels of the same size (size differences not greater than 10 %) are to be vented according to Equations (3) and (4). • The vent areas of different sized vessels have to be brought in relation to a maximum reduced overpressure $p_{red, max} \le$ 1.0 bar. The design overpressure should not fall short of 2 bar. If it is not possible to vent the smaller vessel, then this vessel has to be designed for the maximum explosion overpressure and the vent area of the larger vessel has to be doubled. The use of explosion pressure venting is impossible if the larger vessel cannot be vented this way. In case of pipelines having a nominal diameter DN > 300 experts have to be contacted for advice.	*Coal mill systems always comprise interconnected "vessels"; the mill, separator and dust collector. The duct length will almost always exceed 6 m.* *Pressure Piling = the condition during a deflagration when the pressure increases in the unreacted medium ahead of the propagating combustion zone* *The value 0.2 bar seems to be extremely high for the large vents needed for coal mill ductwork, in which the process creates suction.* *The text on the left is written in bad English and is hard to understand. The German text from which the English text is translated says it more clearly: "Reduced overpressure $p_{red, max}$ must not be allowed to be in excess of 1 bar, whilst the vessels must have a pressure shock resistance of 2 bar g."* *This requirement is impossible to fulfil in conventional filter baghouse design.*
	Coal mills (normally the smaller vessel of the connected vessels made up by the mill and filter baghouse) can neither be vented, nor be built to withstand the maximum explosion overpressure in terms of typical dust specific values for p_{max}. *In-line gravity separators can only be equipped with vents with difficulty. The typical design overpressure of coal mill filter bag houses will be only 0.35 bar (12.5' WG or 5 psi).* *Therefore, it is practically impossible to fulfil this requirement.* *But then, the duct diameter will almost always exceed 300 mm (roughly 12") and its length will almost always exceed 6 m (roughly 20').* *With the mill-to-dust separation duct diameter normally in excess of 300 mm, most coal mill systems would fall in the category where design* "experts have to be contacted for advice"*. Therefore, the applicability of VDI 3673 guidance appears limited.*
Unquote	

Quoted text VDI 3673 (11/2002)	*comments:*
12 Explosion pressure venting of pipelines Dust explosions in pipelines may develop much more violently than in vessels. With increasing pipe length, one must expect detonations with flame velocities up to 2000 $m \bullet s^{-1}$ and local pressure peaks of short duration exceeding 20 bar. The formation of detonations depends upon the pipe diameter and the dust concentration and is more probable with higher K_{St} values of the dust [29 to 32]. Higher pressures may appear at end flanges, reducers and elbows due to pressure piling. Pipelines designed for a nominal pressure of PN 10 will withstand such loadings [5]. In order to keep the reduced explosion pressure in a pipeline comparable to the one in a vented vessel, sections of the pipeline have to be vented radially. The venting is contingent upon the geometry and the strength of the pipe. However this is only feasible for open air installations because of its effects on the surrounding area (Figure 10). Venting of a pipeline in axial direction prevents pressure piling at the end flange. However, the venting has to be done with certified pressure venting devices at least over the entire cross section of the pipe. Rupture disks and explosion doors may be used as pressure venting devices. The static activation overpressure of the pressure venting devices is chosen equal to the vessels in case of radial pressure venting and much higher in case of axial pressure venting, e.g. for a pressure value which is equal to the 50 % value of the pipe strength design.	*In the literature, coal dust and other industrially used ground combustibles are sometimes categorized as incapable of causing a detonation (flame propagation at supersonic speed).* *This will be discussed later.* *Whether flame- and pressure shock wave propagation could reach supersonic velocity in fuel grinding operations typical for the cement industry, is not entirely clear.* *However, the design of non-disintegrating explosion vents of the sizes needed for coal mill systems, and capable of dealing with much lower shock wave velocities, is already a challenge.* *These indicated values for the static activation overpressure seem to be very high. Since indirectly fired coal mill systems will be operated under negative pressure, there is no need for high activation overpressure values.*
Unquote	

NFPA 68 (2002) "Guide for Venting of Deflagrations"
In its chapter 8, the US American Guide NFPA 68 deals with the explosion effects in interconnected vessel configurations, and especially with the effects of long ducts on explosion propagation:

<table>
<tr><th>quoted text NFPA 68 (2002 Edition)</th><th>comments:</th></tr>
<tr><td>Chapter 8 Venting of Deflagrations of Gases and Dusts in Pipes and Ducts Operating at or near Atmospheric Pressure

8.1 Scope. This chapter applies to systems handling gases and dusts and operating at pressures up to 0.2 bar (3 psi). This chapter does not apply to vent discharge ducts. This chapter applies to pipes, ducts, and elongated vesse1s with length-to-diameter ratios of 5 or greater.</td><td>This means that the chapter is applicable to coal mill systems.
Vent discharge ducts are elongated vent channels used to vent an explosion from an enclosure inside a building through the building's wall or roof. They are not related to our topic.</td></tr>
<tr><td>Unquote</td><td></td></tr>
</table>

Sub-Chapter 8.2, § 8.2.1 and § 8.2.2 about Pipes and Ducts

<table>
<tr><th>quoted text NFPA 68 (2002 Edition)</th><th>Comments:</th></tr>
<tr><td>8.2 General.

8.2.1 Several factors make the problems associated with the design of deflagration vents for pipes and ducts different from those associated with the design of deflagration vents for ordinary vessels and enclosures. Such problems include the following:
(1) Deflagrations in pipes and ducts with large length-to-diameter (L/D) ratios can transition to detonations. Flame Speed acceleration increases and higher pressures are generated as L/D increases.
(2) Pipes and ducts frequently contain devices such as valves, elbows, and fittings or obstacles. Such devices cause turbulence and f1ame stretching that promote f1ame acceleration and increase pressure.
(3) Deflagrations that originate in a vessel precompress the combustible material in the pipe or duct and provide a strong flame front ignition of the combustible material in the pipe or duct. Both of these factors increase the severity of the def1agration and the possibility that a detonation will occur.

8.2.2 Compared to the venting of vessels, relatively little systematic test work is published on the design of deflagration venting for pipes and ducts. The guidelines in this chapter are based on information contained in [3], [68 through 76], [105], and [106]. Deviations from the guidelines should provide more vent area than recommended.</td><td>The mill-to-dust collector duct in coal mill systems is such a duct.

Mill-to-dust collector ducts in coal mill plants normally have a high L/D ratio.

This, indeed, also applies to mill-to-dust collector ducts in coal mill plant.

In a coal mill plant, the explosion will normally originate in a "vessel". The vessel is the mill.</td></tr>
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NFPA 85 "Boiler and Combustion Systems Hazard Code", 2001 Edition

The USA NFPA 85 "Boiler and Combustion Systems Hazard Code", 2001 Edition, in its section "Pulverized Fuel Systems", subchapter 6.4, "Design", more particularly § 6.4.6, "Pulverizer System Component Design Requirements", deals with the pressure shock resistance requirements in coal mill plant.

quoted text NFPA 85 (2001 Edition)	*Comments:*
6.4.6 Pulverizer System Component Design Requirements. **6.4.6.1 Strength of Equipment.** **6.4.6.1.1** All components of the pulverized fuel system as described below that are designed to be operated at no more than gauge pressure of 2 psi (13.8 kPa) shall be designed to withstand an internal explosion gauge pressure of 50 psi (344 kPa) for containment of possible explosion pressures. For operating gauge pressures in excess of 2 psi (13.8 kPa), the equipment as described below shall be designed to withstand an internal explosion pressure 3.4 times the absolute operating pressure. **6.4.6.1.2** Equipment design strength shall incorporate the combined stresses from mechanical loading, operating, and explosion and implosion pressures plus an allowance for wear, which shall be determined by agreement between the manufacturer and the purchaser.	*These paragraphs are confusing. They demand 50 psi g or 3.44 bar g pressure shock resistance of "all components of the pulverized fuel system" working at no more than 2 psi g (13.8 kPa), which would be applicable since the "storage firing" mill systems common in the cement industry are operated under negative pressure.* *The maximum dust specific explosion pressure (p_{max}) of the pulverized fuels commonly used in the cement industry is often considerably higher than 50 psi g.* *Therefore, this demand is insufficient and inconsistent, especially in the case of propagation induced additional effects, which are likely to occur as described in VDI 3673 and NFPA 68.* *Either the strength requirements should be increased or explosion vents applied.*
Unquote	

The design strength demanded by § 6.4.6.1.1 without explosion vents being applied is inconsistent, as it is less than the dust specific maximum explosion pressure $p_{max,}$ which would be created by most fuel dust clouds ignited under standard conditions. (See NFPA 68, § 4.2.2.2.) The p_{max} value of a particular fuel should be provided by the supplier and, for some fuels, may also be found listed in specialised publications. Both the p_{max}- and the K_{St} value of a dust (the latter value representing *dP/dt*) can be determined in specialized laboratories, using standardised tests.

quoted text NFPA 68 (2002 Edition)	*Comments:*
4.2.2.2 The maximum deflagration pressure, P_{max}, and rate of pressure rise, *dP/dt (See Annex B)*, are determined by test over a range of fuel concentrations. *(See Annex B.)* The value P_{max} for most ordinary fuels is 6 to 10 times the absolute pressure at the time of ignition.	*This shows that the strength requirements as per NFPA 85, § 6.4.6.1.1 are inconsistent.*
unquote	
Annex B gives additional information on how to measure the indices p_{max} and K_{St}.	

Returning to NFPA 85, chapter 6.4.6.1, the § 6.4.6.1.4 follows, seemingly referring solely to direct firing systems, of which § 6.4.6.1.5 says that no explosion vents should be used on them. § 6.4.6.1.3 is quoted below only for the sake of completeness.

quoted text NFPA 85 (2001 Edition)	*comments:*
6.4.6.1.3 Some parts of the pulverized fuel system, such as large flat areas and sharp corners, can be subjected to shock wave pressures. These pressures shall be included in the design, based on their locations in the system. **6.4.6.1.4** The components falling within the requirements of 6.4.6.1.1, 6.4.6.1.2, and 6.4.6.1.3 for a direct-fired system shall begin at a point that is 2 ft (0.61 m) above the inlet of the raw fuel feeder, at the point of connection of duct work to the pulverizer, and at the seal air connections to the pulverized fuel system. They shall end at the discharge of the pulverizer, external classifier, or exhauster. These components shall include the following and any other associated devices: 1) Raw fuel feeding devices, discharge hoppers, and feed pipes to the pulverizer 2) All parts of the pulverizer that are required for containment of internal pressure 3) Exhauster and connecting pipe from the pulverizer 4) External classifiers and connecting piping from the pulverizer 5) Foreign material-collecting hoppers that are connected to the pulverizer 6) The raw fuel bunker and mechanical components, including but not limited to seals, gears, bearings, shafts, and drives, shall not be required to meet these requirements. **6.4.6.2.1.5** Explosion vents shall not be used on any component of the system that is described in 6.4.6.1.4.	*§ 6.4.6.2.1.4 solely refers to direct-fired systems and, therefore, would not apply to the storage-fired systems common in the cement industry. Storage-fired systems are referred to in paragraphs 6.4.6.1.7 through 6.4.6.1.9. Nevertheless, it makes sense to refer to this paragraph, which mentions all the items upstream of the pulverizer, that, in an analogous way, will also be found in a storage-fired system and, indeed, needs to be pressure shock resistant to the necessary degree.* *The extent of necessary pressure shock resistance downstream of the pulverizer must be seen in the light of NFPA 68, chapter 8, and should enable the system to accept internal pressure considerably higher than 50 psi g (344 kPa = 3.44 bar g) as per § 6.4.6.1. (unless vents were used). See § 6.4.6.1.8.* *§ 6.4.6.1.5 makes sense in the case of a direct-fired boiler system, as long as the flames and pressure shock wave resulting from propagation from the mill towards the burner are contained by the ductwork and dissipate in the large volume of the boiler chamber.*
Unquote	

Then § 6.4.6.1.6 follows, without clarifying whether it refers to either direct firing or storage firing or to both.

quoted text NFPA 85 (2001 Edition)	*Comments:*
6.4.6.1.6 All ductwork from the hot and tempering air supply ducts to individual pulverizers, including damper frames, expansion joints, supports, and hot primary air fans shall be designed to contain the test block capacity of the pulverizer air supply fan. This ductwork is exposed to explosion pressures from the pulverizer in the event of an explosion.	
Unquote	

§ 6.4.6.1.7 clearly does refer to storage firing, and states that:

quoted text NFPA 85 (2001 Edition)	*Comments:*
6.4.6.1.7 If a pulverized fuel storage system is started and operated with an inert atmosphere in all parts of the system in accordance with NFPA 69, *Standard on Explosion Prevention Systems*, the strength requirements of 6.4.6.1.1 shall not apply. Any component of the system that is started and operated with an inert atmosphere shall not be required to comply with the strength requirements of 6.4.6.1.1.	*§ 6.4.6.1.7 refers to an ideal situation that cannot be assumed to be assured under the particular conditions found in cement industry coal mill plants.* *In practice, it would be extremely difficult or costly to guarantee a 100 % failsafe, 24 h/day inert operation, especially during start-ups and stoppages. The vast majority of coal mill plants in the cement industry operate with explosion vents as a last resort protection.* *(See NFPA 69, chapter 2, Oxidant Concentration Reduction, quoted earlier.)*
Unquote	

For the case of cement plant fuel grinding operation, the following § 6.4.6.1.8 must be considered to refer to the generally accepted consequence of the fact that, for storage firing systems, the all-time inert situation is not guaranteed. The paragraph states what parts must then be pressure shock resistant to the extent specified in § 6.4.6.1.1.

Quoted text NFPA 85 (2001 Edition)	*Comments:*
6.4.6.1.8 A pulverized fuel storage system that is not started and operated with an inert atmosphere in accordance with NFPA 69, *Standard on Explosion Prevention Systems*, shall meet the requirements of 6.4.6.1.1. The components falling within these requirements are those described in 6.4.6.1.4, plus any or all of the following which are included in the system: 1) Lock hoppers 2) Circulating fans 3) Transport systems 4) Pulverized fuel feeders 5) Primary air fans handling fuel-laden air 6) Primary air fans if not located downstream of a dust collector that is vented in accordance with 6.4.6.1.9 **6.4.6.1.9** In a pulverized fuel storage system that is not started and operated with an inert atmosphere in accordance with NFPA 69, *Standard on Explosion Prevention Systems*, the following equipment shall meet the requirements of 6.4.6.1.1 or shall be equipped with suitable vents. *(Refer to NFPA 68, Guide for Venting of Deflagrations.)* 1) Cyclone 2) Dust collectors 3) Pulverized fuel bins **6.4.6.1.10** Explosion vents shall not be used on the feeder or pulverizer of any system.	*This is fully applicable to pulverized fuel storage systems as used in the cement industry, since these plants cannot be operated failsafe to the degree needed to fulfil the conditions of NFPA 69.* *NFPA 69's requirements will be fulfilled more easily by industries using smaller process equipment in which blanketing with padding gas (e.g., N_2 or CO_2) could be applied on a continuously monitored and controlled basis.* *The pressure shock resistance requirement as per § 6.4.6.1.1 in § 6.4.6.1.8 would not be consistent with NFPA 68, especially not with chapter 8.* *§ 6.4.6.1.5 (which refers to direct firing) makes no sense in a storage-fired system.* *In almost every coal mill plant, the external classifiers and connecting piping are equipped with at least one explosion vent. This application of explosion venting is basically a sound approach.* *§ 6.4.6.1.9 does not list the mill-to-dust separation (dust collector or cyclone plus dust collector) ductwork.*
Unquote	

The § 6.4.6.1.9 refers to "suitable vents" and to NFPA 68 for further information. Study of the NFPA 68 Guide shows that its chapter 8 is applicable.

NFPA 85's § 6.4.6.1.10 then says: "Explosion vents shall not be used on the feeder or pulverizer of any system." In the general way that this is written, without comment, this is not very informative or helpful. However, in practise there is no need to apply vents directly to a pulverizer and not to its feeder, either.

In this context § 6.4.6.2, “Piping”, first part, is interesting:

quoted text NFPA 85 (2001 Edition)	*comments:*
6.4.6.2 Piping. For systems that are normally operated at a gauge pressure no more than 2 psi (13.8 kPa), the pulverized fuel piping from the outlet of the equipment, as defined in 6.4.6.1.4 and 6.4.6.1.9, to the pulverized fuel burner or storage bin shall comply with 6.4.6.1. Systems that are operated at a gauge pressure greater than 2 psi (13.8 kPa) shall be designed to withstand an internal explosion pressure of 3.4 times the absolute operating pressure.	*Again, the reader is referred to § 6.4.6.1, with its inadequately low strength requirement.*
Unquote	

This is definitely out of line with NFPA 68, "Guide for Venting of Deflagrations", Chapter 8, in which the pressure shock predictions indicate much higher pressure values, for which the plant would have to be provided with the necessary strength.

All in all, these sections of NFPA 85, which are the sections relating to pressure shock resistance and explosion venting, are not of much help for the particular scenario that we are discussing here.

This is because:

- The reference to NFPA 69, "Standard on Explosion Prevention Systems" is, in most cases, non-applicable, due to the fact that practice in a cement Works coal plant creates conditions under which it is impossible to guarantee a permanent internal inert atmosphere.
  Most coal mill plants are designed to be started and operated under inert conditions as stipulated in NFPA 69, "Standard on Explosion Prevention Systems".
  If the inert condition could be guaranteed to a greater extent, then explosion vents as a safety measure "of the last resort" would not be found in coal mill plant all over the world, and coal mill dust explosions would not occur.

As a consequence, the reader is referred to strength requirements, but these are inconsistent with NFPA 68:

- NFPA 68 clearly warns and indicates pressure figures for the duct situations regularly found in coal mill systems. NFPA 85 and NFP 68 are not consistent.

The next stage of our brief study of coal grinding plant must be to look into the different systems. In this context, it is not necessary to examine the many details and differences of existing systems, but we can concentrate on two basic layouts. These are ball mill systems and vertical mill systems. (See fig 5.) Both systems have in common that their modern versions have increased in size, compared with the their ancestors of some 20 years ago, which results in mill-to-separator duct lengths of 20 - 50 times the duct diameter (L/D 20 - 50).

They also have in common the fact that they consist of interconnected vessels. In the layout at the left of fig. 5 (ball mill system), these are the mill chamber, the separator and the product (dust) collector. In the layout on the right of fig. 5 (vertical mill system), these are the mill chamber and the dust collector.

What happens in this kind of plant when a fuel dust explosion occurs?

In most cases, the explosion will be ignited in the mill chamber.
When an explosion occurs in the mill chamber, the following conditions can be established:

1) The conditions of the explosion triangle (fig. 8) are fulfilled.

This implies that the O_2 content in the system (not only in the mill chamber, but rather in the whole duct from mill outlet to dust collector inlet) will allow combustion to take place.

2) The basic conveying velocity of approximately 20 m/s will assist the start of deflagration (which is combustion that propagates as result of “finding” fuel to sustain it).

3) Finely dispersed fuel is present everywhere in the duct between the mill outlet and the dust collector, and its transport takes place under turbulent conditions.

4) The initial ignition causes pressure to build up inside the mill chamber, which is poorly vented.
The reason why the pressure is only poorly vented is that the mill chamber is normally not equipped with explosion vents. It is difficult to include explosion vents in a coal mill design, also, the mill will normally be located inside a building.
The pressure dissipation that takes place is:
a) from the mill chamber into the mill process air inlet
b) from the mill chamber into the mill process air/product outlet (towards the separator/dust collector)
c) via openings in the mill chamber such as the reject chute (vertical mills only)

These ineffective vent channels will not to a great extent contribute to a low or reduced explosion pressure. Therefore, pressure of some significance may develop in the mill chamber, e.g. in the range from 1.5 .- 4 bar g. The maximum specific pressure value p_{max} need not necessarily be reached. The combustion of a dust cloud in a typical mill chamber will rarely proceed under optimal burning conditions. There are no good guidelines available, as far as the prediction of explosion pressure in mill chambers is concerned. Tests would be very difficult and expensive to execute.

The existing guidelines rest, so far, on a conservative ("worst case") approach, as they are based on enclosures without obstructions to inhibit combustion.

There are several reasons to assume that the laboratory defined p_{max} value of a dust/air suspension will not be fully reached in a mill chamber. This, however, is a statement extremely difficult to quantify.
Although the mill chamber will be designed to provide the necessary degree of pressure shock resistance, there is no reason to relax limits. The precompression in the mill provides the starting condition of "elevated initial ignition pressure" for the accelerating explosion propagation towards the next dust separation stage. This is what should concern us.

Fig. 10 shows what would happen if the pressure under which the fuel/air suspension was ignited were elevated to 2 bar, as could be the case if the explosion originated in the mill chamber and then started to propagate through the duct. The pressure in the mill outlet duct, in the earliest stage of propagation through it, would already be much higher than the 2 bar g in the mill and would increase further as the pressure front made its way to the separator(s).

The mill-to-dust separation duct is "open ended", in the sense that it is indirectly connected to the clean air outlet downstream of the fan which provides suction at the outlet of the final dust separation system. The propagation is directed to that point. The pressure shock wave induced by propagation of the explosion would affect the separator more than the mill.

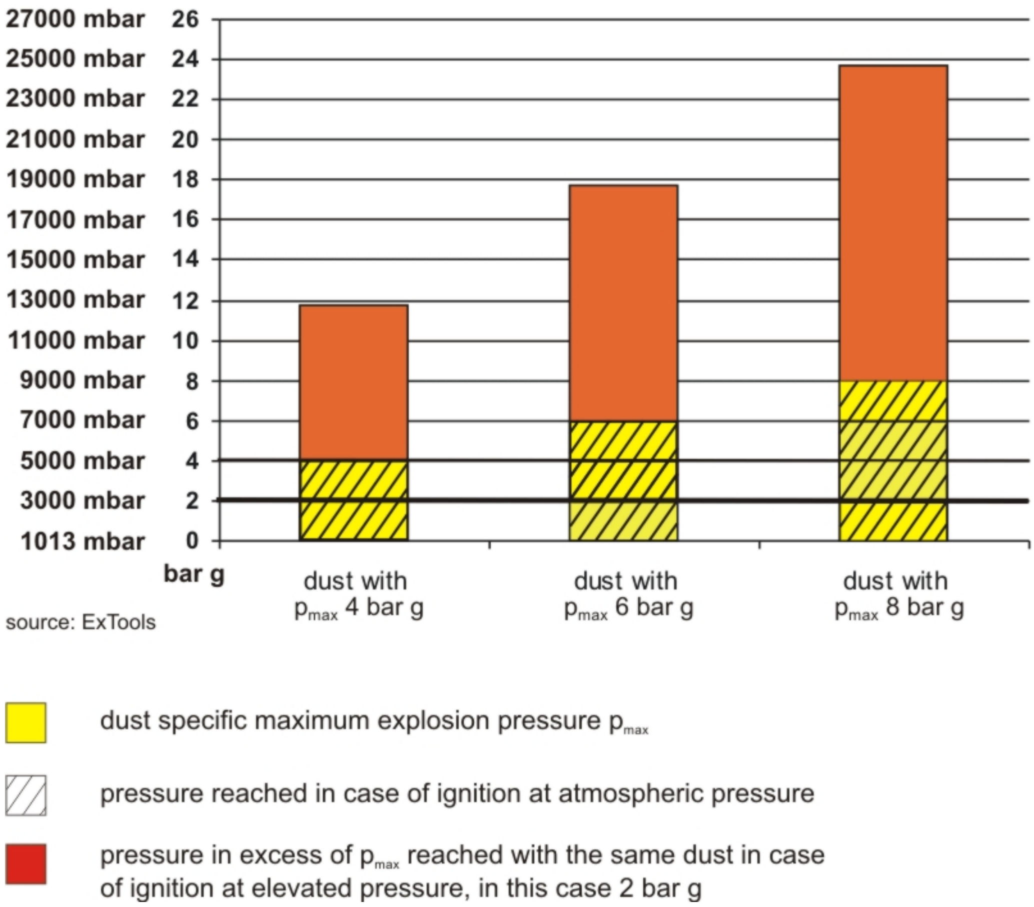


fig.10
difference in pressure reached when ignited under atmospheric- versus elevated initial pressure

Flame propagation causes ignition at an ever higher “elevated” initial pressure, the ignition being caused by the propagating flames which ignite the fuel ahead of the propagating combustion zone, as it “eats” itself into the compressed zone with fuel that is not yet consumed.

The fast propagation “lives” on the strong effects that it creates itself. Pressure piling will, in the final stage, result in flame jet ignition of the unburned particles in the last vessel.
In a coal mill plant, the dust collector is the "last vessel".

A flame jet ignition will normally cause a rate of pressure rise which is so high that explosion vents will not have sufficient time to open and become effective, i.e., vents would not save a dust collector into which a flame propagation would run after having reached a high speed and compressing the internal air by pressure piling.

The pressure build-up would be faster and greater than the capacity of the venting system to release the pressure. The vents would open too late and the bag house would be destroyed by the internal pressure shock. The vents would most likely disintegrate and their parts become lethal missiles. No vent design would be capable of dealing with a flame jet ignition.

Protection against flame jet ignition can only be such that flame jet ignition is avoided, meaning that the speed of the flames and the pressure shock wave in front of the flames are reduced. This knowledge is the reason for the use of so called explosion diverters, which turn aside the explosion pressure shock wave and the main flame ball from the duct before they can enter the downstream separator. The design comprises a bend which will, under normal process conditions, function as quasi 180° bend and, in case of increased pressure, provide an opening in its "knee" through which the shock wave will run into the atmosphere.

The only published information based upon sufficiently closely related scientific work that we have found so far is a 1986 article by B. R. Gardner, R. J. Winter and M. J. Moore, with the title "**Explosion Development and Deflagration-to-Detonation Transition in Coal Dust/Air Suspensions"**. This article describes tests executed under auspices of the CEGB Central Electricity Research Laboratories, Leatherhead, Surrey, England, in a long 350 mm (14") diameter duct under two different sets of conditions.

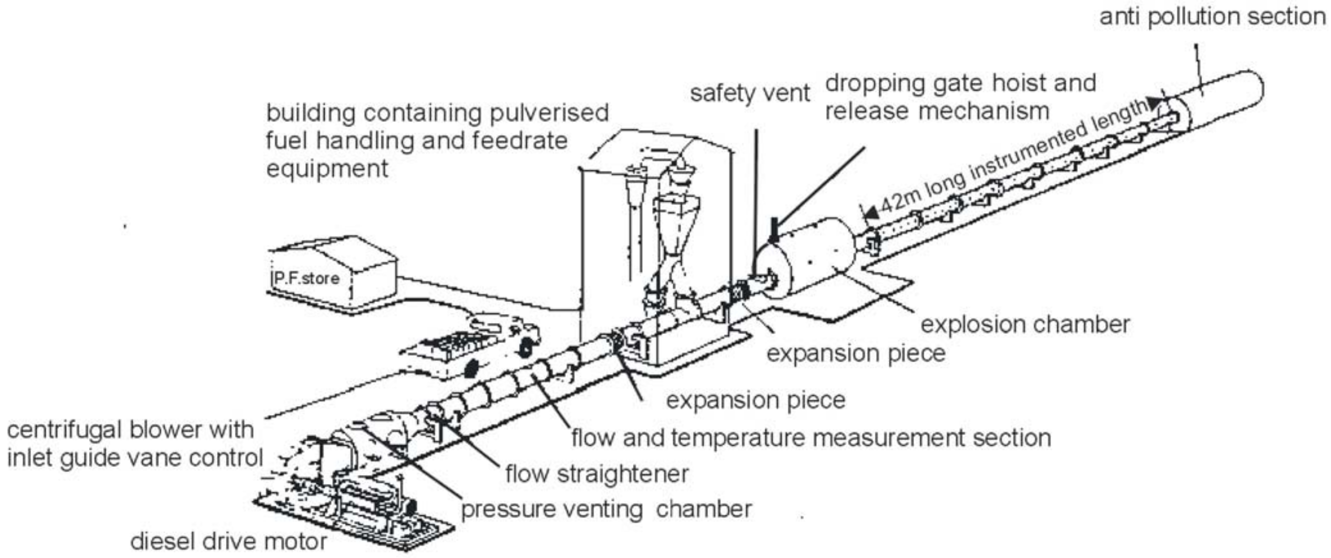


fig. 11
test set-up phase 1 and phase 2 tests

P.F. = pulverised fuel

The phase 1 tests were performed causing an ignition inside the duct, which was open at one end (on the right of the picture). Although it looks as if the duct ends in a special exhauster (called "anti-pollution section"), the duct was simply open at that end.

The phase 2 tests were executed in order to enable a comparison between the pressure at the open end of the duct caused by an ignition inside the integrated chamber with subsequent accelerated propagation, and the pressure achieved at the open end of the duct caused by a "plain" deflagration as reached in phase 1.

The difference was that the ignition taking place in the chamber, with its larger cross section (volume) than a comparable duct length section, caused pre-compression and propagation with subsequent pressure piling towards the open end of the duct.
Configuration and phase 2 test results come quite close to the coal mill configurations that we have discussed already, in which the coal mill is represented by the chamber that formed part of the test duct.

The results show significantly higher pressure values at the end of the duct during the phase 2 tests and are of practical use in so far that, even if in a "real" coal plant the pressure values are lower, they still represent a genuine hazard. It does not really matter whether or not a deflagration develops into a detonation, which means that its speed becomes supersonic. In a coal plant, a speed much less than the detonation speed would be enough to endanger personnel and plant.

Of course, the pressure value figures measured at the end of the duct can be directly translated into pressure shock wave velocity figures.

TABLE
Greatest Test Values of Pressure Rise and Flame Velocity

Coal Type	Nominal[a] Size Grade	Max. Pressure Rise Obtained (P_{max}) bar		Max. Flame Velocity Obtained ms^{-1}
PHASE 1 (PLAIN DUCT) TESTS				
U.K. NCB Type 502	250	0.92		270
	190	0.65		195
	145	0.40		140
	100		NO IGNITION	
	30		NO IGNITION	
U.S. W. Sub-Bituminous	250	1.11		400
	190	0.92		400
	100		NO IGNITION	
PHASE 2 (CHAMBER AND DUCT) TESTS WITH 20 m^3 CHAMBER VOLUME				
U.K. NCB Type 502	250	33.3		2000
	190	24.8		> 1400
	145	9.0		1600
	100	3.3		650
	30		NO IGNITION	
U.S. W. Sub-Bituminous	250	81.5		~2850

fig.12
results from the phase 1 and phase 2 tests

With the different pressures measured for some of the tested coal dusts, if the open end of the duct had been connected with the inlet of a separator, cyclone or dust collector, then this receiving enclosure would certainly have been destroyed by the resulting flame jet ignition.

This is what both the previously mentioned NFPA 68 guide, the NFPA 85 code and the VDI 3673 guidelines warn of, when they speak of interconnected enclosures, pre-compression, pressure piling, elevated initial ignition pressure, duct L/D and deflagration developing into high velocity propagation.

The tests conducted in 1986 have certainly not laid a comprehensive foundation for better guidelines for explosion venting for coal mill systems. They have just contributed to a better understanding of what will happen during propagation under the starting condition of elevated ignition pressure. In order to lay a foundation for improved or new venting and decoupling guidelines enabling engineers to actually build coal mill plants with correct explosion vent implementation, expensive test work of a different character would have to be carried out.

Before test results become standards and official guidelines, they are scrutinised by experts and go through various stages of review.

With this presentation, we have now reached the stage at which we can distinguish correct from incorrect engineering.

It has already been pointed out that plants have become larger and larger over the years, with long mill-to-dust collector ducts as the result. The consequence is that the L/D ratio of the mill-to-dust collector ducts also has increased. Increasing the duct diameter cannot be an option. The required conveying velocity from the mill to the upstream separators and dust collectors must be roughly 20 m/s, and the movement of more air would cost dearly, in terms of capital investment, power consumption and area of filtration medium.

This is where things went wrong, and had to go wrong, as result of the non-availability of applicable, practicable standards.

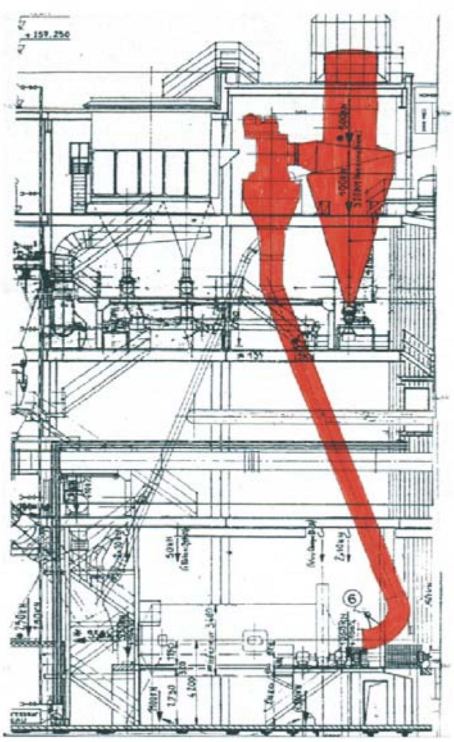


fig. 13
typical examples of incorrect although still quite common configurations for which explosion doors and explosion diverters are specified
a) typical ball mill plant

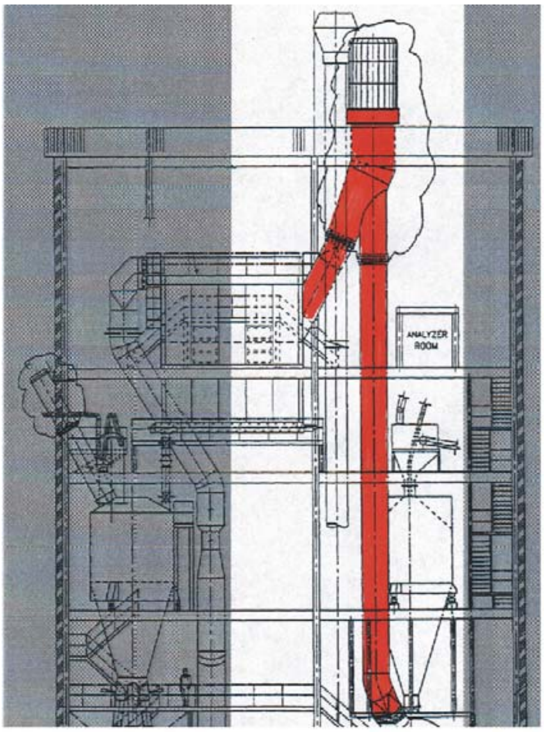


fig. 13
typical examples of incorrect although still quit common configurations for which explosion doors and explosion diverters are specified
b) typical vertical mill plant

Why things went wrong

1. Existing guidelines are related to much smaller systems in other industries. They did not and still do not adequately cover the industrial situation in coal mill plants used in the cement, steel and other industries.

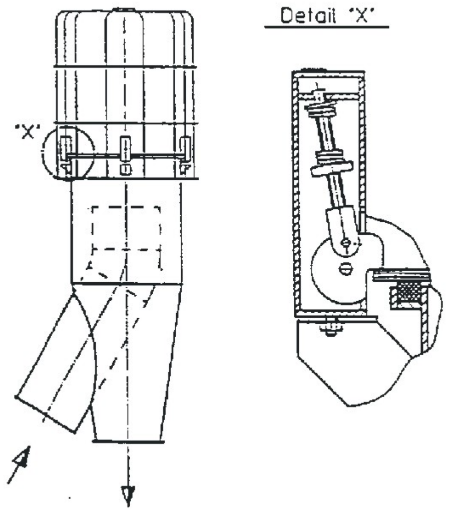
2. The mill itself and the mill system dust collector in new projects often fall within the areas of responsibility of different parties, although the final responsibility may lie with a contractor with sole responsibility for the overall project.

   In many cases, the mill supplier will supply a mill with a sufficient degree of explosion pressure shock resistance, but the duct between the mill and the dust collector may be the responsibility of another party and the dust collector of yet another.

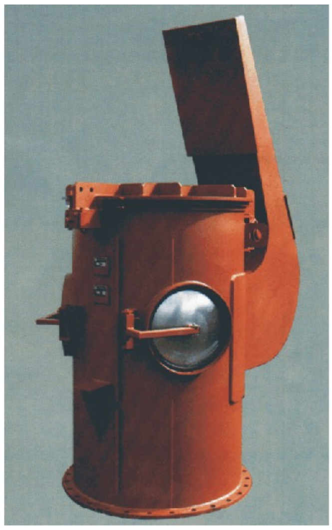
   Strange, unjustifiable requirements can be found, such as ducts being specified as being capable of withstanding 10 bar g internal pressure (NFPA 68 chapter 8, § 8.2.3). Incompatibility between the NFPA 85 and NFPA 68 (USA) guidelines obviously contributes to the confusion.

3. Coal mill dust collectors are often part of the scope of supply of a larger order, which comprises several dust collectors for various sections of a new cement plant. They are more expensive to build than dust collectors for other parts of the cement process plant, because of the requirement that they must be resistant to explosion pressure shock (normally to the degree of 350 - 400 mbar = 3.5 - 4 m WG) and be equipped with explosion vents.
   Given the high competition in this field, there is an understandable reluctance on the part of the dust collector manufacturers to do more than what is felt is absolutely necessary - and exactly what is felt

to be absolutely necessary may vary from company to company (through lack of adequate, practically applicable guidelines).



a) conventional explosion diverter as used at the end of a mill-to-separator duct (= at the inlet of the separator) with cover and bar cage



b) conventional explosion vent with hinged lid, not suitable for duct protection

fig. 14

What is wrong with the incorrect configurations?

1. They enable the propagation of an explosion with its ignition source in the mill chamber through a very long duct. Therefore, the propagation may reach a very high velocity and pressure before the pressure shock wave and flames are finally diverted into the atmosphere, a short distance upstream of the dust collector inlet. See fig. 13.

2. Wherever explosion vents are applied, they will be opened by the energy from the internal pressure of the protected system.
   It has already been discussed that, following the cubic law, the pressure rise velocity in a large enclosure will be lower than in a smaller vessel.
   A dust explosion in a silo will build up the explosion pressure in 100 - 1000 ms, depending on the volume of the silo and other parameters. This is relatively slow. The hinged lid of an explosion door as used on pulverised coal silos will be accelerated and decelerated vigorously, but will still have a few milliseconds to respond and to execute its movement.

   What happens in a mill-to-dust collector duct through which a pressure shock wave propagates with a flame front behind it? The pressure shock wave velocity will increase with duct length.
   When it hits the explosion vent or explosion diverter at the inlet to the dust collector, the velocity (and pressure) in the duct will be high, in some cases considerably higher than 100 m/s (360 km/h).
   The venting element of the explosion vent (the cover or hinged lid) reacting to this pressure shock wave will be accelerated, so as to open within a few milliseconds, much faster than it ever would have to open if it were used as a vent on a silo.

   In some cases, some vents at the end of a long coal mill-to-dust collector duct have worked fine: their relatively light cover went off and was caught by the bar cage, just as it was supposed to be.
   But in some other cases, the whole bar cage was ripped off and fell down, although of considerable mass, after having been accelerated and becoming a projectile.

How come that sometimes it works fine and sometimes it does not?

The answer to this question is that explosion propagation - for a number of reasons and quite unpredictably - will not always reach the velocity at which the vent is destroyed.

It must be noted that explosion venting concepts should be based upon a worst case approach. A basic requirement for explosion vents is that they do not disintegrate into parts that turn into missiles for a particular application for which they have been selected.

3. For years, explosion vents on ducts have been designed without the reclosing feature due to difficulties in connection with the design of low-mass, reclosing, reusable explosion vents, related to inertia, acceleration and deceleration.

   The reclosing capability, which would be most easily to accomplish by means of hinged constructions, would offer the feature of protection against ingress of atmospheric air in the aftermath of a venting event. It would therefore provide effective fire damage limitation but it is extremely difficult to design.

   The acceleration, deceleration and centrifugal forces are extremely difficult to handle when a hinged vent is opened by a fast pressure shock wave that propagates through a duct. The opening movement will be extremely fast and the acceleration of the moving parts from zero to maximum velocity will take place in such a short time that the parts are exposed to enormous forces.

Why are these incorrect configurations still being offered?

1. The guidelines on how to deal with the matter are not clear.
   Ducts are made as long as they need to be to transport ground fuel from the mill, via the separator stage(s) into the storage silo. Explosion venting concepts are basically copies of previously executed versions.

2. Non-reclosing, non-reusable vents are cheaper than reclosing, reusable vents with hinged covers, and they are generally thought of as having no mass-related problems.
   The general assumption "free of mass-related mechanical problems due to low mass" is wrong. It all depends on the pressure shock wave velocity at which the venting element is hit.
   Because it is known that, on long ducts, the mass or inertia of a vent is extremely important when it comes to vents that have to open in almost zero time, not many engineers have seriously tried to install hinged vents at the end of long ducts. Those who did so have run - and are still running – considerable risks concerning a basic requirement, namely, that the vent, in the case of a venting incident, must function without disintegrating and forming missiles.

   Hinged vents will normally have a heavier venting element (lid) than vents with a simple cover. In the case of fast propagation, they are likely to fail the non-disintegration requirement.

   It has been found that vents with low mass, non-reclosing, non-reusable venting elements are less prone to damage than explosion vents with a hinged lid. Although the venting element will be destroyed, it can be trapped in a simple bar cage. The bar cage will be safer in terms of possible disintegration than an explosion vent with a hinged lid.
   However, this is only true as long as the propagation velocity through the duct does not exceed certain values, for which no reliable calculation methods exist.

3. Non-reclosing, non-reusable vents are easier to apply than reclosing, reusable vents with hinged covers, since they are generally thought of as being free of mass-related problems.
   Due to the problems of mass inertia with vents at the ends of long ducts, and due to the fact that dust collector suppliers (who, in many cases are responsible for the explosion diverter at the dust collector inlet) need to sell at competitive prices, the explosion vent or explosion diverter at the dust

collector inlet is often supplied with a non-reclosing, non-reusable venting element. This is cheaper in terms of initial investment.

Such designs were tested in Germany many years ago in a very limited range of sizes.
At the time that the designs were tested, the mill-to-dust collector ducts of coal mill systems commonly had a much lower L/D ratio. From today's point of view, the "type test certification" must be considered outdated, since unfortunately, type certification has never put any emphasis on the degree of pressure rise velocity that the vents are actually exposed to at the end of a long duct.
The mechanical strength of the design (avoiding disintegration) has been tested without putting much emphasis on the dynamic effects of d*P*/d*t*, because the venting covers were of low mass and "beyond doubt".
So, the high velocity phenomena have not been looked into sufficiently for this certification to be considered as valid for ducts with an L/D as commonly found in modern coal mill plant.
Not much further development work has been done in this field. On non-reclosing explosion diverters and other non-reclosing vents for ducts, there is no more recent type test certification available.
The result is that, although the cover and bar cage design is not suitable for hard hits by pressure shock waves with a very high velocity, these explosion diverters do have a certificate, however outdated, and will be offered by suppliers. However, this certificate is no longer within the realm of the European Community ATEX directives, where new, comprehensive product certification covering the intended use will soon be required.

4. <u>Non-reclosing, non-reusable vents are not a disadvantage to their supplier, but they are for the often unknowing operator.</u>

One of the consequences of this continued use of an old, often copied design is that it is still quite common to use non-reusable explosion vents that do not reclose.

The disadvantage is that, after a venting has occurred, there is an opening in the duct close to the dust collector inlet, which – at least initially, until the isolating valve has been closed – remains open. In addition to this, the venting openings of the bag house would remain open if the bag house was equipped with rupture disks (which are also non-reclosing, non-reusable explosion vents).

The fan at the clean air end of the dust collector will suck atmospheric air into the bag house as long as it is not shut off or isolated from the dust collector.

All this will cause delay in fire damage mitigation. The fire in a bag house, which must be expected to start in the aftermath of the (successfully vented) explosion, will be supported by the ingress of atmospheric air.

For dust collector suppliers, who have already had the benefit of the cheaper components being used for vents, this is an additional advantage. On top of having built equipment at lower manufacturing costs, greater damage must be expected to occur in the event of an explosion. Greater damage means that repair and refurbishment will require more spare parts, which must be bought by the plant, normally under tremendous pressure from time requirements, leaving few choices other than turning to the OEM, who may demand a premium price for extra fast supply.

What can be done? What is the solution to the problems?

1. Decide that reclosing, reusable vents should be used. They are available.

   Not many people would like a pulverised fuel silo with one (or more) non-reclosing, non-reusable explosion vents on top.
   After having been exposed to excess internal pressure, it would be impossible to inert the silo with CO_2 or N_2, or to fight an internal fire, e.g. by covering it with raw meal. Blowing raw meal into an open silo would cause a mess. Therefore, explosion doors will be used as vents on silos in the majority of cases.

   For the same reason as one would equip a pulverised coal silo with reusable, reclosing explosion vents, the mill-to-separation stage duct and the separators should be equipped with reusable, reclosing explosion vents.

   As previously discussed, it is the mass-related or inertia-related problems that caused engineers to refrain from using reclosing, reusable explosion vents on mill-to-separator stage ducts, in favour of using low-mass, non-reclosing, simple devices.
   This is understandable with regard to the fact that the ducts are long, which results in a high L/D (length/diameter) ratio and, as a consequence, in high velocities of pressure shock waves. See VDI 3673, chapters 3, 11 and 12 and NFPA 68, chapter 8.

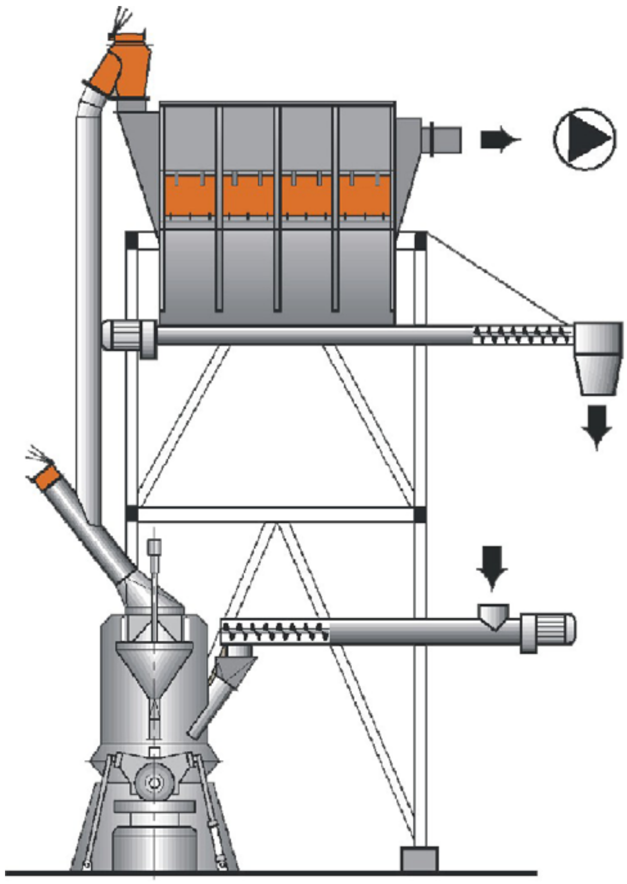
   However, due to the fact that the plants have become larger over the years, these considerations have lost their relevance. With present mill-to-separation stage duct lengths resulting in an L/D ratio $\geq$ 40 - 50, the mass problem becomes the central issue. Any cover, with the exception of vent covers in the form of plastic foils or similar low mass devices, would have too much mass to be safe when undergoing such acceleration as caused by a pressure shock wave hit of, say, 100 m/s
   (360 km/h).

   In spite of these mass and inertia related problems, this raises the question of how to use hinged venting elements, which tend to have even more mass than non-reclosing, non-reusable ones. The answer:

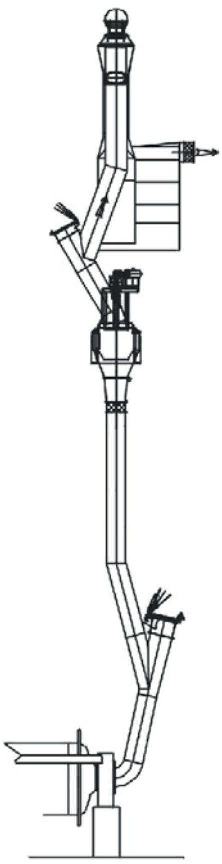
2. Position the vents in such a manner that the pressure shock does not reach a dangerous velocity.

   The principle is simple. Position the explosion vents strategically. Positioning a first vent close to the source of the real hazard is the decisive point.
   If positioned correctly, this vent will inhibit precompression: the essential support to the start of fast deflagration propagation.

   The solution is shown in fig. 15:



a



b

fig.15 correct implementation of vents, examples
a) in vertical mill system
b) in ball mill system with dynamic separator

As discussed, it is this precompression, the explosion pressure created in the mill chamber – the most likely location for an initial ignition in the system – which essentially stimulates the propagation to gain velocity over the distance through which it propagates.

Of course, this concept works properly only if the starting propagation is actually diverted out of the system. The vent close to the mill outlet must be positioned in such a manner that the deflagration pressure pulse immediately follows a definite direction after leaving the mill outlet. It should follow the axis of the duct in order to be diverted correctly.

This requirement, and the fact that the necessary duct diversion implies an increased cross section in the split section, make it necessary to carefully engineer the diversion and the position of the vent. The increased cross section with the inherent drop in air velocity will have an affect on particle transport, when enough speed has just about been gained to take particles away from the mill on their way to the separator stage.

Other design requirements are that the diversion should not enable the formation of coal deposits, and that the venting element should be either wear protected or positioned so as not to be hit by abrasive particles.

Further requirements are that the reclosing, reusable vent located in this position offers at least the same cross section as the duct, is capable of dealing with high velocity pressure shock hits, and that the reaction forces are dealt with appropriately.

Although the L/D ratio of the duct between the mill outlet and the first vent – Vent #1 – is relatively low, the velocity of the starting propagation might already have increased, and the venting element could be hit hard.
The latter requirement demands that the hinged lid of the vent be of low mass.

Last, but not least, the vent path must be free of obstacles, and personnel should not come close to a vent blast, which will be accompanied by strong pressure and flames, affecting the vent vicinity.
This aspect clearly demands attention at the earliest planning stage. The position of the mill and ductwork in the mill building must be selected in order to provide a fee venting path.

3. <u>Further complete the concept by means of a vent at the separator inlet.</u>

Cyclones and dust collectors count as separators with an inlet at which a vent can be positioned. Static and dynamic separators used in ball mill plants need a different kind of venting protection. (See fig. 15b and below.)
The vent at the inlet of the separator - Vent #2 - has the task of diverting a deflagration, which propagates through the duct, between Vent #1 and the separator inlet to the atmosphere.
It would normally be constructed to a design known as an explosion diverter. An explosion diverter is a duct-integrated tubular section, which forms either a 167.5° or a 150° bend. Under normal process conditions, the air/fuel dispersion will follow the bend.
In case of explosion propagation, the pressure shock wave will open an aperture in the "knee" of the bend, through which it will be vented into the atmosphere. Such diverters now can be equipped with reclosing, reusable vents.

Downstream of Vent #1, a propagation towards the separation section would still be possible, since the flames from the initial explosion in the mill may not have been diverted completely out of the duct via Vent #1, and since the fan at the clean end of the dust collector may suck such remaining flames into the upward tract of the duct. A subsequent ignition of residual dispersed coal dust could well cause a secondary propagation towards the separator inlet.

This propagation, however, would be harmless in terms of flame speed and pressure wave velocity, which would remain slow. It lacks the precompression factor which would have supported the propagation and which would have caused it to be much faster had Vent #1 not been in place.
The length of this stretch of ducting, or its L/D, is of lesser importance, due to Vent #1.

Important considerations in this context are: Optimal positioning in terms of diversion of the explosion pressure shock wave and the flame front, clearance in terms of freedom from personnel presence and obstacles, wear, transition of the airflow into the separator (e.g., with decreased velocity or split into two dust collector inlets) and reaction forces.

In ball mill systems with an intermediate separation stage, the "Vent #1 + Vent #2 concept" should be implemented in an analogous way. (See fig. 15b.)
Separators (including cyclones) are enclosures, although not always with large volumes.
In a typical storage firing coal mill plant they are interconnected "vessels", under the terms of VDI 3673 and NFPA 68, since they are connected with the coal mill. As such, special explosion venting rules apply, which are not very well specified in the guides and codes.
Both the VDI 3673 and the NFPA 68 guidelines give no clear and practically usable instructions for cases in which an explosion propagates from the coal mill into another vessel (the separator).

VDI 3673, chapter 11 refers you to "experts" in such a case, without specifying who the experts are and where they can be found.

Following the logic of the Vent #1 + Vent #2 concept, for the straightforward concept of vertical mills with a direct duct connection between the mill outlet and the dust collector inlet, the problem can be reduced to the following:

A cyclone can be installed with an explosion vent at its inlet, which will protect it against pressure piling and subsequent precompression caused by an approaching, propagating deflagration.

This vent would reduce pressure in the cyclone. This reduction would follow the rules for explosion pressure reduction by means of explosion venting **on the basis of "ignition at near atmospheric initial pressure"**.
Therefore, following the standard instructions and equations for the calculation of required vent area as per VDI 3673 and NFPA 68, this would mean that the cyclone will have to be equipped with one or more explosion vents for the reduction of its internal explosion pressure. However, this will have **no function in the diversion of the explosion shock wave**, which propagates through the duct. The vents would have to be positioned on top of the cyclone enclosure.

A dynamic or static separator cannot be installed with an explosion vent at its inlet. The product flow comes from below and should run in line with the central axis of the conical separator enclosure, at least for the last few meters before it enters the conical enclosure.

Another aspect of the configuration of a ball mill with a separator is that the separator cannot be positioned too closely to the mill outlet. It must sit higher up, since the rejects have to be conveyed towards the relatively distant ball mill inlet, in order to undergo the grinding process once again. This conveying is often accomplished via a simple gravity system with a steeply inclined fall pipe.
This fact, together with the requirement of entering the separator via a straight vertical central duct of several meters' length, implies that there will be a certain distance from the mill outlet to the separator inlet - therefore, a large L/D ratio.
Installing Vent #1 would solve the latter problem.

The role and correct positioning of Vent #1 in ball mill systems are very important. The reduction of pressure piling and precompression effects in the separator depend entirely upon the reliability with which Vent #1 will take the velocity out of the propagation.

Again, the separator would have to be protected against a deflagration on the basis of "ignition at near atmospheric initial pressure" and have to have its explosion vents.

This deflagration would then be of the "ignition at near atmospheric initial pressure" quality, for which explosion venting as per VDI 3673 or NFPI 68 would be the correct method of protection.
Quite often this is not easy to achieve, since the form of such an enclosure is not generally well-suited to the implementation of explosion vents, and since the separator will, in many cases, be positioned somewhere in a building where a cleared vent path is difficult to provide.
In the case of dynamic separators, the rotor assembly will make explosion venting even more difficult to achieve.

The solution to this problem is shown in fig. 15 b. It is a combined solution, and the function of the diverter vent at the outlet of the separator is twofold.

a) In the case of an explosion venting occurrence, it disconnects the separator from the dust collector downstream.
b) It acts as an enclosure vent in the sense of VDI 3673/NFPA 68.
   Since the factor "volume", as an input to the calculation of the required vent area, is low (due to the fact that the separators have a only a small volume), the required vent area for the enclosure venting function will be relatively small.
   In most cases, the required vent area for the "enclosure vent function" will not exceed the cross section of the separator-to-dust collector duct. Therefore, the functions 1 and 2 can be combined conveniently in one vent: in this case, a vent in a diverting position on a Y-piece. This double function will work, provided that the position of the diverting vent is close to the separator outlet.

The final section towards the dust collector and the implementation of the explosion diverter at the inlet of the dust collector will be similar to other systems.

4. <u>Finalisation of the concept, regarding the bag house.</u>

The concept with reclosing, reusable explosion vents is completed by mounting explosion doors on the bag house. There are various ways to optimise this procedure. The higher the pressure shock resistance of the bag house, the less the required vent area.

It is worthwhile looking into possibilities to increase the strength of bag houses. The use of reclosing, reusable explosion vents will result in a higher investment cost if the vent area is not reduced.
Greater bag house strength resulting in less vent area could very well compensate for the higher investment, in terms of cost per unit of vent area.

Thorwestern Vent's "vent # 1 + vent # 2" concept's self-reclosing vent # 1 (explosion door)

Thorwestern Vent's "vent # 1 + vent # 2" concept's self-reclosing vent # 2 (explosion diverter)

Summary

The multiple vent concept has so far been realised in a significant number of new plants, as well as in a number of retrofit situations. It continues to become an accepted standard with an increasing number of reputed cement engineering companies. Presently it is the only concept which sequentially follows the logic of the guidelines and their intentions to promote safety. The details, however, are poorly suited to the particular practical situation of coal grinding in the cement industry. This is mainly due to the fact that the experts writing these guidelines are not familiar with the size a such a plant can reach today. The equipment for realisation of this concept is readily available.

The guides and codes VDI 3673, NFPA 68 and NFPA 8503 cannot satisfy engineers dealing with explosion vents for coal mill plants. The guidelines do not relate to industrial practice and to the scale of today's modern, large systems. The VDI 3673 guidelines will soon have to be read as a guidance for compliance with the standards presently under development with the European Community Standardisation Committees CEN TC 305 WG 3 SG 5, -SG 2 and -SG 6.

The effects of duct-integrated explosion vents close to coal mill outlets must be investigated more thoroughly before the solution offered in this presentation can become part of modified guidelines and codes. Investigation by means of test work is foreseen and may become part of a CEN-funded program aiming at enhancing knowledge in the field of industrial explosion protection.